

BROADBAND ECLIPSE SPECTRA OF EXOPLANETS ARE FEATURELESS

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ABSTRACT

Spectral retrieval methods leverage features in emission spectra to constrain the atmospheric composition and structure of transiting exoplanets. Most of the observed emission spectra consist of broadband photometric observations at a small number of wavelengths. We compare the Bayesian Information Criterion (BIC) of blackbody fits and spectral retrieval fits for all planets with eclipse measurements in multiple thermal wavebands—typically hot Jupiters with 2–4 observations. If the published error bars are taken at face value, then eight planets are significantly better fit by a spectral model than by a blackbody. In this under-constrained regime, however, photometric uncertainties directly impact one’s ability to constrain atmospheric properties. By considering the handful of planets for which eclipse measurements have been repeated and/or reanalyzed, we obtain an empirical estimate of systematic uncertainties for broadband eclipse depths obtained with the Spitzer Space Telescope: $\sigma_{\text{sys}} = 5 \times 10^{-4}$. When this systematic uncertainty is added in quadrature to published uncertainties, the Bayesian evidence for spectral features disappears: blackbodies have better BIC for all planets. Stratospheric inversions, high C/O ratios, disequilibrium chemistry, and He-dominated atmospheres have been inferred from spectral features in broadband eclipse photometry, and are therefore suspect. We conclude that statements about atmospheric composition and structure based solely on photometry are premature.

Subject headings: planets and satellites: atmospheres — techniques: photometric

1. INTRODUCTION

An exoplanet on an edge-on orbit periodically passes behind its host star. The decrement in thermal flux that occurs during such an eclipse is a measure of the dayside brightness temperature of the planet at that wavelength. The brightness temperature of a planet varies with wavelength because of the wavelength-dependent opacity and vertical temperature profile of the atmosphere.³ If different wavelengths probe the same atmospheric layer (e.g., a cloud deck) then the planet will appear to have a blackbody spectrum. In the absence of clouds, a planet may still have a blackbody spectrum if the atmospheric layers probed are isothermal.

At sufficiently high spectral resolution, we do not expect any planet to emit like a blackbody, because molecular absorption lines dictate that the atmospheric opacity varies dramatically between neighboring wavelengths and temperature cannot be isothermal throughout the atmosphere. So far, however, the vast majority of eclipse measurements have been broadband photometry.

In principle, the detection of molecular bands in the infrared emission spectrum of a planet enables the retrieval of greenhouse gas abundances and the vertical temperature profile of the planet. A typical retrieval model uses 10 parameters to describe the atmospheric composition and vertical temperature profile (Madhusudhan & Seager 2009), while a typical hot

Jupiter has only been observed in 2–4 thermal broadbands. The retrieval problem is thus under-constrained.

A widely noted consequence of the parameter-data mismatch is that exact atmospheric properties cannot be uniquely determined. This has not stopped researchers, however, from placing interesting limits on certain parameters (principally C/O ratios and the presence of temperature inversions; Madhusudhan et al. 2011), and from finding trends between these atmospheric properties and those of the host star (Knutson et al. 2010).

The more troubling aspects of under-constrained retrieval are that (1) there is no way to reject erroneous measurements, and (2) the estimated uncertainties on eclipse depths directly affect the uncertainties on atmospheric parameters. This is in stark contrast to typical over-constrained problems such as fitting an occultation model to time-series data, for which it is normal to σ -clip the data, and for which the uncertainties on individual data are largely irrelevant (indeed photometric uncertainties are typically estimated in the process of fitting a model to the data, rather than taken on faith).

2. BROADBAND ECLIPSE SPECTRA

A search on exoplanet.org combined with a careful literature review yields 42 exoplanets with published photometric eclipse measurements for at least two thermal wavelengths (longward of $1 \mu\text{m}$). They are: CoRoT-1b, CoRoT-2b, GJ 436b, HAT-P-1b, HAT-P-2b, HAT-P-3b, HAT-P-4b, HAT-P-6b, HAT-P-7b, HAT-P-8b, HAT-P-12b, HAT-P-23b, HD 149026b, HD 189733b, HD 209458b, KELT-1b, Kepler 5b, Kepler-6b, Kepler-12b, Kepler-17b, TrES-1b, TrES-2b, TrES-3b, TrES-4b, WASP-1b, WASP-2b, WASP-4b, WASP-5b, WASP-8b, WASP-12b, WASP-14b, WASP-17b, WASP-18b, WASP-19b, WASP-24b, WASP-33b, WASP-43b, WASP-48b, XO-1b, XO-2b, XO-3b, and

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³ Even if each location on the planet has a blackbody spectrum, the overall spectral energy distribution will not formally be a blackbody because different locations have different temperatures, but this is a minor effect.

XO-4b (due to the limit of 50 references for Letters, we list recent papers that cite all of the original results: Cowan & Agol 2011; Désert et al. 2011a,b; Fortney et al. 2011; Anderson et al. 2011; Todorov et al. 2012; Stevenson et al. 2012; Knutson et al. 2012; Crossfield et al. 2012; Smith et al. 2012; Blečić et al. 2013; Zhou et al. 2013; de Mooij et al. 2013; Lewis et al. 2013; Todorov et al. 2013; Beatty et al. 2013; Baskin et al. 2013; Cubillos et al. 2013; O’Rourke et al. 2014).

Since we are merely concerned with the emergent spectra of the bodies, it is immaterial if a planet is on an eccentric orbit (GJ 436b, HAT-P-2b, XO-3b) or even if it is a highly-irradiated brown dwarf (KELT-1b). The majority of these observations—in particular, all those at 3.6, 4.5, 5.6, 8.0, and 24 μm —were made with the Spitzer Space Telescope (Werner et al. 2004).

We fit a blackbody spectrum to the eclipse depths for each planet using the published transit depth and stellar effective temperature. We assume symmetric, Gaussian, error bars for the eclipse depths; in the few cases where asymmetric error bars were published, we take the mean of the upper and lower error bars.

The transit depth and stellar effective temperature have associated uncertainties that are important if one is trying to estimate the planet’s bolometric flux, but these errors tend to have a gray impact on the planet’s spectrum and hence we optimistically neglect them for the current analysis.

In the interest of simplicity, we also ignore the detector spectral response functions and instead compute the Planck function at the central wavelength of each photometric observation. Moreover, by using the stellar effective temperature rather than a detailed stellar model, we are treating the star as a blackbody. For broadband measurements in the infrared these assumptions are reasonable.

3. THE SIGNIFICANCE OF SPECTRAL FEATURES

In order to quantify the significance of spectral features, we turn to the Bayesian Information Criterion (BIC; Schwarz 1978). The BIC is a simple way to compare the goodness-of-fit of models with different numbers of parameters: $BIC = \chi^2 + k \ln N$, where k is the number of free parameters and N is the number of data. It is similar in spirit to the reduced χ^2 in that it penalizes models with many parameters, but it remains well-defined when there are fewer data than there are parameters (as is the case for hot Jupiter photometric eclipse retrieval). As a baseline, we compute the BIC for each planet in our sample by fitting a blackbody to each planet and adopting the quoted uncertainties (the only unknown is the blackbody temperature, so $k = 1$).

The blackbody BIC values are plotted in Figure 1 against the number of wavelengths available for each planet. The black lines denote the quality of the blackbody fit: the solid line is a good fit ($\chi^2/N = 1$), while the dashed line is a perfect fit ($\chi^2 = 0$). Planets that lie above the solid black line are poorly fit by a blackbody. The dashed red line is $BIC = 10 \ln N$, where $k = 10$ is representative of an idealized spectral retrieval model that can perfectly fit the observations (i.e., $\chi^2 = 0$). The solid red line shows the same but assuming a more realistic goodness-of-fit: $\chi^2/N = 1$.

Planets that lie above the red lines show Bayesian evidence of spectral features according to the following rule of thumb: $\Delta BIC < 2$ is not worth more than a bare mention, $6 < \Delta BIC < 10$ is strong evidence, and $\Delta BIC > 10$ is very strong (Kass & Raftery 1995).

If published eclipse values and uncertainties are taken at face value, then a handful of hot Jupiters have broadband emission spectra that demand a full spectral retrieval: CoRoT-2b, GJ 436b, HAT-P-8b, HD 189733b, HD 209458b, WASP-1b, WASP-8b, and WASP-12b. The bulk of hot Jupiters, however, lie below the red lines, implying that the data do not warrant spectral retrieval.

4. EMPIRICAL ESTIMATE OF ECLIPSE UNCERTAINTIES

For a handful of the best and brightest targets, multiple *Spitzer* observations have been obtained with the same instrument.⁴ These observations are listed in Table 1. For any reshoot or reanalysis, we list the discrepancy between the new measurement and the original published value.

The published uncertainties are too low, but by how much? If we demand that 68% of repeated measurements fall within the 1σ error bars, then we obtain an empirical eclipse uncertainty of 4.7×10^{-4} . This value is greater than every single quoted uncertainty in the table (let alone the Poisson noise limits), so we conclude that it is a systematic uncertainty. Given the small number statistics, we round the above value to a single significant figure, and adopt it as our estimate of systematic error in broadband photometric eclipse measurements with existing facilities: $\sigma_{\text{sys}} = 5 \times 10^{-4}$.

5. BROADBAND SPECTRA IN THE FACE OF SYSTEMATIC ERRORS

In Figure 2 we revisit the distribution of blackbody BIC vs. N_λ in light of systematic errors. We add the systematic uncertainty of $\sigma_{\text{sys}} = 5 \times 10^{-4}$ in quadrature to the quoted uncertainties to obtain realistic error bars and recompute the BIC for each planet.

All planets lie below the blue line, meaning that there are no planets for which a spectral retrieval is warranted. The two planets that are worse fit by a blackbody are CoRoT-2b and WASP-1b. It is worth noting that the emergent spectrum of CoRoT-2b is also poorly fit by any 1D atmospheric models (Deming et al. 2011), while the observations of WASP-1b are still under review (Wheatley et al. 2010).

6. DISCUSSION

It is worth summarizing why observers tend to underestimate eclipse depth uncertainties. First and foremost, the instruments being used are being pushed orders of magnitude beyond their design specifications. This is easy to see in the raw photometry, which suffers from detector systematics that are comparable to, and sometimes dwarf, the astrophysical signal of interest. It is routine to remove these detector systematics so effectively that the quoted uncertainties are within 10–20% of Poisson (photon-counting) noise.

⁴ For the most part, the initial observations only covered the secondary eclipse, whereas later observations spanned half or a full orbit. In other cases, multiple eclipses were obtained to look for astrophysical variability.

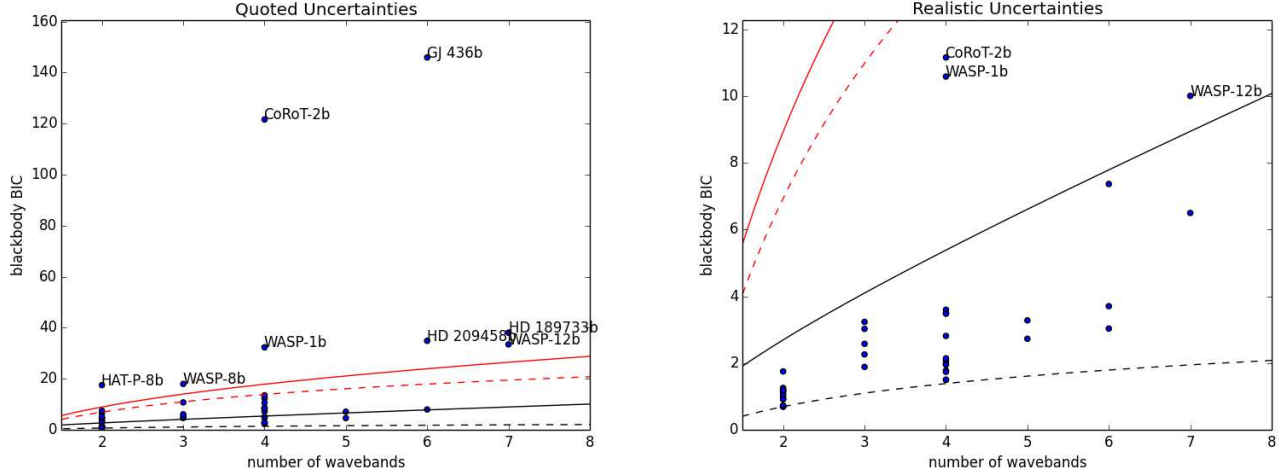


FIG. 1.— The Bayesian Information Criterion (BIC) of a blackbody fit is plotted against the number of wavebands for which photometric eclipse measurements have been obtained; each blue dot represents one of the 42 transiting planets in our sample. The left panel uses the published uncertainties for each planet, while the right panel adds an empirically-determined systematic error of $\sigma_{\text{syst}} = 5 \times 10^{-4}$ in quadrature to each eclipse measurement. The red lines show the BIC one would obtain by fitting the data with a 10-parameter spectral retrieval model (the solid line is a good fit: $\chi^2/N = 1$; the dashed line is a perfect fit: $\chi^2 = 0$). The black lines denote the quality of the blackbody fit: the solid line is a good fit ($\chi^2/N = 1$), while the dashed line is a perfect fit ($\chi^2 = 0$). Planets that lie above the solid black line are poorly fit by a blackbody. Planets that lie above the red lines warrant a full spectral retrieval.

TABLE 1
Spitzer ECLIPSE RESHOOTS AND REANALYSES

Planet	Wavelength	Value	Uncertainty	Discrepancy ^a	Reference
HD149026b	8.0 μm	8.4×10^{-4}	1.0×10^{-4}		Harrington et al. (2007)
		4.11×10^{-4}	7.6×10^{-5}	4.3×10^{-4}	Knutson et al. (2009)
		5.2×10^{-4}	6.0×10^{-5}	3.2×10^{-4}	Stevenson et al. (2012)
HD189733b	3.6 μm	2.56×10^{-3}	1.4×10^{-4}		Charbonneau et al. (2005)
		1.466×10^{-3}	4.0×10^{-5}	1.1×10^{-3}	Knutson et al. (2012)
	4.5 μm	2.14×10^{-3}	2.0×10^{-4}		Charbonneau et al. (2005)
		1.787×10^{-3}	3.8×10^{-5}	3.5×10^{-4}	Knutson et al. (2012)
GJ 436b	8.0 μm	3.91×10^{-3}	2.2×10^{-4}		Charbonneau et al. (2005)
		3.44×10^{-3}	3.6×10^{-5}	4.7×10^{-4}	Agol et al. (2010)
		5.4×10^{-4}	8.0×10^{-5}		Stevenson et al. (2010)
WASP-12b	3.6 μm	4.52×10^{-4}	2.7×10^{-5}	8.8×10^{-5}	Knutson et al. (2011)
		3.79×10^{-3}	1.3×10^{-4}		Campo et al. (2011)
		4.19×10^{-3}	1.4×10^{-4}	4.0×10^{-4}	Crossfield et al. (2012)
		3.3×10^{-3}	4.0×10^{-4}	4.9×10^{-4}	Cowan et al. (2012)
WASP-12b	4.5 μm	3.63×10^{-3}	4.4×10^{-4}	1.6×10^{-4}	Crossfield et al. (2012)
		3.82×10^{-3}	1.9×10^{-4}		Campo et al. (2011)
		4.24×10^{-3}	2.1×10^{-4}	4.2×10^{-4}	Crossfield et al. (2012)
		3.9×10^{-3}	3.0×10^{-4}	8.0×10^{-5}	Cowan et al. (2012)
		4.29×10^{-3}	3.3×10^{-4}	3.9×10^{-4}	Crossfield et al. (2012)
		5.0×10^{-3}	4.0×10^{-4}	1.2×10^{-3}	Cowan et al. (2012) ^b
		5.5×10^{-3}	4.4×10^{-4}	1.7×10^{-3}	Crossfield et al. (2012) ^b

NOTE. — ^aMagnitude of discrepancy between an observation and the original published value. ^bThe “null hypothesis” fit for which ellipsoidal variations are fixed to zero. This is approximately equivalent to analyzing the eclipse in isolation, as was done in Campo+(2012).

It is undeniable that careful calibration can help make up for an imperfect instrument, but if it was really possible to extract Poisson-limited performance out of a systematics-riddled instrument, then there would be no advantage in building better instruments: astronomers would content themselves with large light buckets. The real uncertainties must lie in between the detector systematic noise ($\sim 10^{-2}$ for IRAC) and the Poisson limit (5×10^{-5} for the brightest hot Jupiter systems).

With more repeat observations it might be possible to make separate systematic error estimates for each tele-

scope+instrument combination, but there is no evidence that these errors are grossly different for the various instruments on *Spitzer*. This is unsurprising since the magnitude of detector effects for IRAC and MIPS are all at about the 1% level, and none of these systematics are entirely understood.

The secondary sources of systematic errors are correlated parameters and conditional solutions. Correlated parameters can be accounted for by running a Markov Chain Monte Carlo (MCMC) and marginalizing over nuisance parameters; this has become standard in the

field. “Conditional solutions” refers to the fact that the best-fit parameters are obtained given many assumptions that are not varied as part of the MCMC: aperture, sky pixels, σ -clipping scheme, detector and astrophysics parametrization, lack of binary companion or accretion disk, etc. The choices made by researchers are defensible, but adopting a reasonable meta-parameter is similar to slicing through correlated parameters: it invariably leads to under-estimated error bars.

When one is pushing instruments two orders of magnitude beyond their specifications, the most robust measurements are those repeatedly made, and analyzed by multiple distinct groups. It is possible to push well beyond the systematic noise floor and eventually to establish a firm value with robust error bars.

It should be noted that there is still science to be done using broadband eclipse photometry, even in the presence of systematic uncertainties. The orbital phase of eclipse places useful constraints on orbital eccentricity and hence planet formation/migration scenarios (Charbonneau et al. 2005). Moreover, dayside bolometric flux can be readily estimated, since integrating noise is less damning than differentiating it. In fact, the systematic errors involved in bolometric flux estimates are small for hot Jupiters precisely because these planets have approximately blackbody spectra (Cowan & Agol 2011). The dayside effective temperature of a planet, in turn allows us to infer Bond albedo and/or heat transport.

In light of this study, spectral resolution offers two significant advantages over photometry: (1) a high-resolution emission spectrum is more likely to deviate significantly from a blackbody, and (2) the retrieval problem is over-constrained. This bodes well for current and

future efforts to perform *bona fide* emission spectroscopy.

7. CONCLUSIONS

The retrieval of parameters from disk-integrated broadband photometry hinges on planets not looking like blackbodies. If published uncertainties are taken at face value, then many of the brightest hot Jupiters have distinctly non-blackbody broadband spectra.

In order to perform under-constrained spectral retrieval, however, it is critical to have believable error bars. One can empirically check the accuracy of published error estimates by considering the measurements that have been replicated. We performed this comparison and found that the empirical 1σ systematic uncertainty in broadband eclipse depths is approximately 5×10^{-4} . If one combines this uncertainty with published eclipse measurements, then all hot Jupiters are featureless, including the brightest targets. We conclude that statements about atmospheric composition based solely on broadband emission measurements are premature. Temperature inversions and odd compositions were inferred for short period planets based on photometric eclipse spectra. Our results calls these phenomena into question. Undoubtedly, many planets have stratospheric inversions and interesting chemistry, but there is no robust evidence for this in the photometry of short-period exoplanets.

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REFERENCES

- Agol, E., Cowan, N. B., Knutson, H. A., et al. 2010, *Astrophysical Journal*, 721, 1861
- Anderson, D. R., Smith, A. M. S., Lanotte, A. A., et al. 2011, *MNRAS*, 416, 2108
- Baskin, N. J., Knutson, H. A., Burrows, A., et al. 2013, *Astrophysical Journal*, 773, 124
- Beatty, T. G., Collins, K. A., Fortney, J., et al. 2013, *ArXiv e-prints*, arXiv:1310.7585
- Blecic, J., Harrington, J., Madhusudhan, N., et al. 2013, *Astrophysical Journal*, 779, 5
- Campo, C. J., Harrington, J., Hardy, R. A., et al. 2011, *Astrophysical Journal*, 727, 125
- Charbonneau, D., Allen, L. E., Megeath, S. T., et al. 2005, *Astrophysical Journal*, 626, 523
- Cowan, N. B., & Agol, E. 2011, *Astrophysical Journal*, 729, 54
- Cowan, N. B., Machalek, P., Croll, B., et al. 2012, *Astrophysical Journal*, 747, 82
- Crossfield, I. J. M., Barman, T., Hansen, B. M. S., Tanaka, I., & Kodama, T. 2012, *Astrophysical Journal*, 760, 140
- Cubillos, P., Harrington, J., Madhusudhan, N., et al. 2013, *Astrophysical Journal*, 768, 42
- de Mooij, E. J. W., Brogi, M., de Kok, R. J., et al. 2013, *A&A*, 550, A54
- Deming, D., Knutson, H., Agol, E., et al. 2011, *Astrophysical Journal*, 726, 95
- Désert, J.-M., Charbonneau, D., Fortney, J. J., et al. 2011a, *ApJS*, 197, 11
- Désert, J.-M., Charbonneau, D., Demory, B.-O., et al. 2011b, *ApJS*, 197, 14
- Fortney, J. J., Demory, B.-O., Désert, J.-M., et al. 2011, *ApJS*, 197, 9
- Harrington, J., Luszcz, S., Seager, S., Deming, D., & Richardson, L. J. 2007, *Nature*, 447, 691
- Kass, R. E., & Raftery, A. E. 1995, *Journal of the American Statistical Association*, 90, 773
- Knutson, H. A., Charbonneau, D., Cowan, N. B., et al. 2009, *Astrophysical Journal*, 703, 769
- Knutson, H. A., Howard, A. W., & Isaacson, H. 2010, *Astrophysical Journal*, 720, 1569
- Knutson, H. A., Madhusudhan, N., Cowan, N. B., et al. 2011, *Astrophysical Journal*, 735, 27
- Knutson, H. A., Lewis, N., Fortney, J. J., et al. 2012, *Astrophysical Journal*, 754, 22
- Lewis, N. K., Knutson, H. A., Showman, A. P., et al. 2013, *Astrophysical Journal*, 766, 95
- Madhusudhan, N., & Seager, S. 2009, *Astrophysical Journal*, 707, 24
- Madhusudhan, N., Harrington, J., Stevenson, K. B., et al. 2011, *Nature*, 469, 64
- O’Rourke, J. G., Knutson, H. A., Zhao, M., et al. 2014, *Astrophysical Journal*, 781, 109
- Schwarz, G. 1978, *The Annals of Statistics*, 6, pp. 461
- Smith, A. M. S., Anderson, D. R., Madhusudhan, N., et al. 2012, *A&A*, 545, A93
- Stevenson, K. B., Harrington, J., Nymeyer, S., et al. 2010, *Nature*, 464, 1161
- Stevenson, K. B., Harrington, J., Fortney, J. J., et al. 2012, *Astrophysical Journal*, 754, 136
- Todorov, K. O., Deming, D., Knutson, H. A., et al. 2012, *Astrophysical Journal*, 746, 111
- . 2013, *Astrophysical Journal*, 770, 102
- Werner, M. W., Roellig, T. L., Low, F. J., et al. 2004, *ApJS*, 154, 1

- Wheatley, P. J., Collier Cameron, A., Harrington, J., et al. 2010,
ArXiv e-prints, arXiv:1004.0836
- Zhou, G., Kedziora-Chudczer, L., Bayliss, D. D. R., & Bailey, J.
2013, *Astrophysical Journal*, 774, 118